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PARAMETRIC ENGINE STUDY FOR A MACH 0.98 COMMERCIAL AIR TRANSPORT

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ABSTRACT

A preliminary parametric engine study was made for a Mach 0.98 advanced technology transport using the supercritical wing. Advanced engine weight technology compatible with a mid-decade introduction into commercial service was used for the three-engine, 300-passenger airplane of this study. A takeoff gross weight of 386 000 pounds was selected to provide a range of about 3000 nautical miles. Fan pressure ratios FPR from 1.50 to 2.25 and takeoff turbine-inlet temperatures T_4 from 2460 to 2860° R were considered. Significant improvements in range were obtained by raising the FPR over this spectrum when bypass ratio BPR and overall pressure ratio OPR were optimized. An increase in T_4 over the spectrum considered here had much less effect on range than an increase in FPR. Neither the approach nor the (lift-off) sideline noise requirements of F.A.R. Part 36 could be met with any of these engines without acoustic treatment of the nacelles. Even with acoustic treatment, only one-stage fan engines could meet the approach requirement for the maximum suppression of 15 PNdB assumed in this study. Unfortunately, FPR must therefore be limited to about 1.7. With this constraint, BPR optimizes near 4, and OPR optimizes between 25 and 30 when a takeoff T_4 of 2660° R is selected with a turbine-cooling bleed representative of present-day technology. It was assumed through most of the study that the aircraft could be area-ruled so that total aircraft drag remained constant as the engine cycle parameters were changed.

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SUMMARY

A preliminary parametric engine study was made for a Mach 0.98 advanced technology transport using the Whitcomb supercritical wing. Advanced engine weight technology was incorporated in the three-engine airplane of this study. A takeoff gross weight of 386 000 pounds was selected to provide a range of about 3000 nautical miles for this 300-passenger airplane.

Point-design engine performance calculations were made for cruise, but some simplifying approximations were made to determine the takeoff operating conditions. Also, differences in range and total fuel consumption during climb and letdown were ignored between the various engines considered in this study. Despite these approximations, it is felt that the resulting trends are valid and point the way toward selection of an engine.

As fan pressure ratio FPR was increased over the spectrum from 1.50 to 2.25, range (the airplane figure of merit) increased by 300 to 400 nautical miles. Optimum bypass ratio BPR and sea-level-static total airflow decreased while optimum overall pressure ratio OPR remained nearly constant. An increase in T_4 had much less effect than an increase in FPR for the span of temperature considered here (i.e., takeoff T_4's from 2460 to 2860° R). The range improvement with higher T_4 is greatest at higher FPR's and also increases as turbine cooling schemes are improved.

Neither the approach nor the lift-off sideline noise requirements of F.A.R. Part 36 could be met with any of these study engines unless the nacelles were acoustically treated. Even then, only one-stage fan engines could meet the approach noise requirement for the maximum suppression of 15 PNdB assumed in this study. With only one fan stage, FPR is limited to about 1.7. This limitation is unfortunate because of the significant range improvement that can be obtained with higher FPR's. With an FPR of 1.7, BPR optimizes at about 4 and OPR optimizes between 25 and 30 when a takeoff T_4 of 2660° R is selected with a turbine-cooling bleed

representative of present-day technology. Higher T_4's are not particularly beneficial unless significant improvements can be made in turbine-cooling technology.

INTRODUCTION

The supercritical wing proposed by Whitcomb (ref. 1) offers the potential for delaying the transonic drag rise experienced by present-day subsonic jet transports as their flight speed approaches Mach 1. Transport airplanes using this wing could then cruise at somewhat higher speeds than in present commercial use with little or no penalty in lift-drag ratio.

This report presents a parametric engine study that was made for an advanced technology transport using the supercritical wing concept. Present-day airframe weights and engine component efficiencies were used in this study along with engine weights representative of mid-decade introduction into commercial service. A cruise speed of Mach 0.98 was selected somewhat arbitrarily as that which would push the speed almost to the limit without being too far up on the drag rise curve. The airplane was sized to carry 300 passengers a range of approximately 3000 nautical miles. Takeoff gross weight was fixed throughout the study at 386 000 pounds. The operating empty less podded engine weight was fixed at 180 000 pounds. As the engine design parameters were changed, both the specific fuel consumption and engine weight changes that were obtained were reflected as a change in range. Range was used as the airplane figure of merit. The engines were sized at cruise from a point design calculation. At takeoff, engine cycle parameters were estimated so that engine thrust and noise could be calculated.

The purpose of the study is to determine the optimum engine design parameters for this particular airplane. The optimum design parameters may be influenced by the noise limits imposed by Federal Air Regulation Part 36. Noise levels both from the jet streams and the fan turbomachinery were estimated at lift-off and approach. Range penalties introduced by inlet and duct treatment for alleviating turbomachinery noise were also estimated.

Only a three-engine configuration was studied. Bypass ratio and overall pressure ratio were optimized for maximum range at each value of fan pressure ratio that was considered. Fan pressure ratio was varied from 1.50 to 2.25. Turbine-inlet temperatures during takeoff were varied from 2460 to 2860° R - both with and without turbine cooling.

Changes in engine diameter were calculated as the design parameters were changed. For the major part of the study, however, the airplane lift-drag ratio was assumed to remain unchanged despite these engine dimensional changes. This is probably an optimistic assumption, but might be approached by re-area-ruling the airplane each time engine size is changed. As a perturbation to the basic study, engine drag was allowed to change with diameter from its reference value for one series of cases. Changes in engine drag were reflected as changes in airplane lift-drag ratio for these cases.

SYMBOLS

BPR	bypass ratio
c_s	speed of sound, knots (naut mi/hr)
C_L	lift coefficient
D	drag, lb
F_N	net thrust, lb
FPR	fan pressure ratio
L	lift, lb
M	Mach number
OEW	operating empty weight, lb
OPR	overall pressure ratio
R	range, naut mi
sfc	specific fuel consumption, (lb fuel/hr)/lb thrust or hr^{-1}
S_{wing}	wing planform area, ft^2
T_4	turbine-inlet temperature, $^{\circ}R$
TOGW	takeoff gross weight, lb
$\dot{W}_A$	total engine airflow, lb/sec
$W_{end\ cr}$	airplane gross weight at the end of cruise, lb
W_{eng}	installed weight of 3 engines, lb
W_G	takeoff gross weight, lb
$W_{start\ cr}$	airplane gross weight at the start of cruise, lb

$\beta_{turb\ cool}$ turbine cooling bleed chargeable to cycle, percent of core airflow

Subscripts

cr cruise

ref reference

sls sea-level-static

T.O. takeoff

METHOD OF ANALYSIS

Selection of Takeoff Gross Weight and Airframe Weight

It was desired to select a takeoff gross weight (TOGW) that gives a range of about 3000 nautical miles for a wide-body airplane which is designed to carry 300 passengers.

Figure 1 shows how the operating empty weight (OEW) varies with TOGW for turbofan-powered subsonic transports either now flying or soon to be flying. Data points shown were obtained from reference 2. It was assumed that the airplane of this study could be located on this weight curve. An iterative procedure was used to determine the TOGW of this study airplane.

To begin the iteration, a TOGW was arbitrarily assumed. The OEW was then found from figure 1. The payload of 60 000 pounds (300 passengers at 200 lb each) was then added to the OEW. The total fuel load was obtained by subtracting this sum from the TOGW that was assumed. The mission fuel was assumed to be 82 percent of the total fuel thus calculated. (18 percent of the total fuel load is held in reserve.) 20 000 pounds of fuel was assumed to be used during a 200-nautical-mile climb up to cruise. The airplane weight at the start of cruise, then, was the TOGW minus 20 000 pounds. The weight at the end of cruise was the difference between the TOGW and the mission fuel with the letdown fuel added back in. The letdown fuel was assumed to be 2000 pounds. These weights at the beginning and end of cruise were then substituted into the Breguet range equation

$$R_{cr} = \frac{(L/D)(M)(c_s)}{sfc} \ln \frac{W_{start\ cr}}{W_{end\ cr}} \tag{1}$$

Present-day subsonic jet transports have cruise L/D ratios (excluding engines) in the order of 20. In the absence of experimental data, it was assumed for this study that the cruise L/D of a transonic (Mach 0.98) airplane employing a supercritical wing is 18.5. Additional drag due to engines was also included, as discussed in the next section. An sfc of 0.70/hour (representative of installed sfc for a high-bypass-ratio engine) was used in the iteration. Total range was obtained by adding the 200-nautical-mile climb range and the assumed 150-nautical mile letdown range to the cruise range obtained from the Breguet equation.

The preceding calculation was repeated, as necessary, by assuming a new value of TOGW until a total range of 3000 nautical miles was obtained. After several iterations it was found that a TOGW of 386 000 pounds and an OEW of 220 000 pounds satisfied this condition.

After finding the correct TOGW and OEW, it was then necessary to subtract the installed engine weight to find the airframe weight (i.e., OEW minus podded engine weight). Airframe weight and TOGW were then fixed for the remainder of the study so that the total fuel weight would vary as the engine weight changed.

Podded engines of existing weight technology were found to weigh about 13 300 pounds each when sized at 40 000 pounds sea-level-static thrust. By subtracting the weight of three of these engines from the OEW of 220 000 pounds, it was found that an existing-technology airframe would weigh 180 000 pounds. The airframe weight was then fixed at this value for the study airplane.

A sketch of this conceptual study airplane is shown in figure 2. The engines are located at the rear to provide as clean a wing as possible in order to achieve a high L/D at cruise.

Engines

The long-duct, separate-flow (unmixed) exhaust turbofan engines of this study were sized for cruise. A sketch of a typical engine pod is shown in figure 3. Sound deadening material is shown both in the duct walls and in the inlet walls and centerbody surface. In addition, an inlet ring concentric with the centerbody and outer wall is shown with sound deadening material.

Engine cycle calculations were made at cruise for a range of engines with fan pressure ratios FPR varying from 1.50 to 2.25. Bypass ratio BPR and overall pressure ratio OPR were optimized for maximum range at each FPR. Three levels of cruise turbine-inlet temperature T_4 were considered - in 200° R increments from 2260 to 2660° R. Two turbine cooling bleed schedules were used. One, which was highly optimistic, had no bleed. In the other, which is representative of today's technology, chargeable bleed is assumed to vary linearly with takeoff T_4, as shown in figure 4. Chargeable bleed is less than actual bleed. As defined here, it is the equivalent amount that could be bled from the compressor discharge and dumped back into the main stream past the turbines to give the same turbine discharge conditions that really occur when actual bleed is used and some turbine work recovery is obtained.

In addition to cruise, cycle calculations were also made at both sea-level-static and Mach 0.23 lift-off conditions after making some simplifying assumptions about engine operation at these conditions. Takeoff and lift-off T_4's were assumed to be 200° R higher than the cruise T_4's. In other words, takeoff T_4's of 2460, 2660, and 2860° R were considered. Another assumption made in this study was that the sea-level-static full power total corrected airflow at the fan face was 92 percent of the cruise corrected airflow. This airflow assumption is based on empirical data for existing high BPR engines tested at conditions simulating both the Mach 0.98 cruise condition at 40 000 feet and sea-level takeoff (presuming no changes in exhaust-nozzle areas).

Other assumptions made in this study were that BPR, OPR, and FPR remain unchanged from takeoff to cruise. These assumptions, too, are supported by empirical data correlating the values of these variables between takeoff and the cruise condition of this study. Other engine parameters were fixed for all engines at all flight conditions, as summarized below:

Fan adiabatic efficiency	0.83
Compressor adiabatic efficiency	0.85
Combustor efficiency	0.985
Inner turbine adiabatic efficiency	0.90
Outer turbine adiabatic efficiency	0.91
Inlet pressure recovery	1.00
Pressure ratio across combustor	0.94
Total pressure ratio in fan duct from fan discharge to nozzle	0.96
Total pressure ratio in core from low-pressure (outer) turbine discharge to nozzle	0.98
Exhaust nozzle thrust coefficient (both streams)	0.985

One of the constraints to be examined in this report is the approach noise at one nautical mile from the runway threshold. Engine thrust was reduced to a low level commensurate with an assumed L/D of 5.5 at an approach speed of 135 knots (Mach 0.203). A typical approach weight for the airplanes of this study was about 299 000 pounds. If it is assumed that the airplane angle of attack is 10° and the altitude is 370 feet (based on a 3° glide slope), the net thrust required is about 12 000 pounds per engine. This is equivalent to about one-third of the takeoff thrust. To determine the engine operating parameters needed to calculate both jet noise and fan turbomachinery noise during approach, a computerized turbofan performance program capable of part-power calculations (ref. 3) was used. This program uses scaled fan, compressor, and turbine maps in determining part-power operating conditions. Approach was the only condition where exact part-power calculations were required in this simplified study.

Uninstalled engine weight was allowed to vary with the sea-level-static BPR, OPR, total airflow, and T_4, as described by Gerend and Roundhill (ref. 4). They have also correlated engine weight with the year of first flight. It was assumed that the engines of this study would first fly in the year 1974. The additional weight for installation (including inlet, nacelle, and nozzle) was assumed to be 3.13 times the total airflow at takeoff. This incremental installation weight is based on empirical data for existing high-bypass-ratio engines used in large commercial transports.

The sum of total fuel weight and installed engine weight was constant in this study, since TOGW, payload, and airframe weight were constant. As engine weight changed, therefore, total fuel weight also changed. Total fuel weight is one of the most important variables in this study where range is used as the figure of merit. The other major factor, of course, is cruise sfc. Cruise range was calculated from the Breguet range equation (eq. 1), which can be expressed as

$$R_{cr} = 561 \frac{L/D}{sfc} \ln \frac{366\ 000}{268\ 000 + 0.82\ W_{eng}} \quad \text{(nautical miles)}$$

when

$$M = 0.98$$

$$c_s = 573 \text{ knots (n. mi./hr)}$$

$$W_{start\ cr} = 366\ 000 \text{ lb}$$

$$W_{end\ cr} = 268\ 000 + 0.82\ W_{eng}$$

The airplane weight at the start of cruise is simply the TOGW minus the 20 000 pounds of fuel that was assumed to be used during takeoff and climb up to cruise. The airplane weight at the end of cruise was obtained by subtracting the mission fuel from the TOGW and adding the 2000-pound letdown fuel back in. (Mission fuel is

82 percent of the total fuel, which is the difference between the TOGW and the sum of the airframe weight (fixed at 180 000 lb), payload (fixed at 60 000 lb), and installed engine weight.)

Total range, as described in the section on TOGW selection, was assumed to be 350 nautical miles greater than the cruise range for all cases. This increment is composed of the 200-mile climb and the 150-mile letdown ranges.

Engine diameters and lengths were computed by the method of reference 4. A preliminary estimate of nacelle drag as a function of diameter is given in figure 5. This schedule of drag, which assumes some degree of favorable interference, is employed in a later part of the study. However, unless otherwise stated, the majority of the calculations are based on the optimistic assumption that the engines can be area-ruled into the fuselage so successfully that nacelle drag does not vary with engine diameter (and is fixed at the nominal value given by fig. 5 for a diameter of 80 in).

Noise Constraints

Noise calculations were made for two measuring points, both of which are specified in Federal Air Regulation Part 36. They were:

(1) Sideline noise measured immediately after lift-off on a 0.25-nautical-mile (1520-ft) sideline on the ground at the angle of maximum noise.

(2) Approach noise, when the airplane is 1 nautical mile from the runway threshold, measured on the ground directly under the glide path at the angle of maximum noise. The airplanes of this study were assumed to be at an altitude of 370 feet at this measuring station (i.e., a 3° glide slope).

For an airplane having a TOGW of 386 000 pounds, F.A.R. Part 36 specifies a noise limit of 106.5 EPNdB for both of the above measurements. A third measurement specified by this regulation should be made at a point 3.5 nautical miles after the start of takeoff roll on the extended runway centerline. If the altitude exceeds 1000 feet, the thrust may be reduced to that required for a 4 percent climb gradient or to maintain level flight with one engine out, whichever thrust is greater. The noise limit at this measuring station for the airplane weight considered here is 104 EPNdB. This noise measurement was ignored in this study because it was felt that with the high BPR engines considered herein it would be possible to gain altitude quickly after takeoff. (High BPR engines (BPR $\geqq$ 2), sized for the cruise condition in this report, generally have takeoff thrust-to-gross-weight ratios F_N/W_G superior to existing low BPR, turbofan-powered transports.) The higher altitude should provide considerable noise attenuation. Also, the high thrust level available at takeoff should permit a considerable reduction in thrust at the 3.5-mile point where the climb gradient is reduced. The reduction in thrust will reduce the level of noise generated at any given altitude.

Total perceived noise has two components - jet noise from the two jet streams and fan turbomachinery noise. Jet noise, measured in PNdB, was calculated by standard methods described by the Society of Automotive Engineers in references 5 and 6. Jet noise is primarily dependent on the exit velocities of the two flow streams, but is also affected by the gas flow rates and the flow areas. These variables were calculated at both Mach 0.23 (152 knots) after lift-off at full thrust and with thrust cut back to 12 000 pounds per engine during approach at Mach 0.203 (135 knots).

Fan turbomachinery noise, also measured in PNdB, is a function of many things - for example, spacing between stator and rotor, tip speed, number of stages, fan pressure ratio, thrust, and amount of nacelle acoustic treatment. In this study, it was assumed that the engines would be built with optimum stator-rotor spacing without any inlet guide vanes in order to minimize noise. Curves developed by the Propulsion Systems Acoustics Branch at NASA-Lewis* relate fan machinery noise to FPR for both one- and two-stage fans with and without suppression. These noise curves were scaled from a net thrust of 90 000 pounds and a measuring-point distance of 1000 feet to both the approach and sideline conditions of this report. In addition to logarithmic thrust and distance-squared scaling, extra air absorption due to a change in slant range (ref. 5) was included. The curves which result for the approach condition are shown as figure 6. Total noise at both takeoff and approach conditions was obtained by adding logarithmically the machinery and jet noise, as described in reference 5 for multiple noise sources.

The noise calculations made in this study are in units of PNdB. The F.A.R. Part 36 requirements, however, are stated in terms of EPNdB. The EPNdB scale (where E stands for effective) is a modification of the PNdB scale where a correction is made to account for (1) subjective response to the maximum pure tone and (2) the duration of the noise (ref. 7) heard by the observer. These modifications to the PNdB scale were ignored in this study, since the amount of information known about the maximum tones and directivity of the noise from these parametric engines is rather limited. It is thought that the error introduced by ignoring these modifications is less than the error that might occur by making further assumptions about the noise sources.

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* Presented at Aircraft Propulsion Conference, NASA Lewis Research Center, November 18-19, 1970, by a panel chaired by James J. Kramer, Chief of Propulsion Systems Acoustics Branch at Lewis Research Center.

Fan machinery noise can be attenuated by acoustically treating the inlets and ducts. According to figure 6 and information supplied by the Propulsion Systems Acoustics Branch at NASA-Lewis, acoustic treatment can reduce this noise as much as 15 PNdB. The ducts of the turbofan engines of this study are long (see fig. 3), so they readily lend themselves to wall treatment with a porous sound-absorbing sandwich material such as that described in reference 8. Duct and inlet wall treatment and an acoustically lined splitter ring inserted in the inlet were found in reference 9 to penalize the weight of a Pratt & Whitney JT3D engine about 370 pounds. Much of this weight penalty is undoubtedly tied up in structural modifications since the lining material by itself is very light. This amount of treatment on the JT3D engines of a DC8 airplane lowered the approach noise about 11 PNdB. Since most of the treatment weight is applied near the periphery of the engine, an approximate weight scaling calculation for larger engines is to multiply the 370-pound penalty of the JT3D by the diameter ratio of the larger engine to the JT3D's diameter of 53 inches. The addition of one splitter to the inlet of some of the high BPR engines of this study may not be as effective in reducing approach noise of these engines as it was for the low-BPR JT3D because of the larger inlet diameter-to-sound-wave length ratio (ref. 10). If a single splitter ring is placed in the inlet, it is estimated that it will be most effective if placed about 8 inches from the wall. It was estimated in this study that this type of inlet and duct treatment combined will reduce the fan machinery noise about 10 PNdB. The full 15 PNdB reduction, which was assumed in this study to be the maximum possible, could be attained only by the addition of more splitter rings in the inlet. No assessment of the additional weight penalty was made for these extra splitter rings.

RESULTS AND DISCUSSION

Engine Cycle Optimization Without Turbine Cooling Bleed

A typical plot of installed (no nacelle drag) cruise performance for the non-mixed flow turbofan engines of this study is shown as figure 7. This particular plot is for an FPR of 1.50 and a cruise T_4 of 2460° R (corresponds to a takeoff T_4 of 2660° R). Although not presented herein, similar plots could be made from the data generated in this study for other FPR and T_4 combinations. It can be seen from figure 7 that sfc can be reduced by increasing BPR with OPR fixed for this particular FPR and T_4. Likewise, it can be seen that sfc is reduced by increasing OPR with BPR fixed. Unfortunately, both of these otherwise favorable trends tend to reduce the cruise specific thrust F_N/W_A. Reduced F_N/W_A means that engine total airflow must be increased to overcome the cruise drag for which all engines in this study were sized. Enlarging the airflow tends to increase the engine diameter which in turn tends to increase both drag and weight. In addition, increasing the OPR by itself tends to increase engine weight without any consideration of the airflow effect, since more compressor stages are required.

Using the BPR = 4, OPR = 24 point of figure 7 as a reference, the effect of changes in cruise T_4, OPR, BPR, and FPR has been plotted in figure 8(a-d). The effects of changing OPR and BPR were obtained from figure 7. The effects of changing T_4 and FPR were obtained by examining additional plots similar to figure 7 for other FPR's and T_4's. Figure 8(a) shows that increasing the cruise T_4 is a mixed blessing performance-wise because the sfc rises at the same time that F_N/W_A is increasing. Figure 8(b) shows that increasing the OPR up to a maximum of about 36 causes a small decrease in the sfc with only slight reductions in F_N/W_A. Figure 8(c) shows that increasing the BPR decreases the sfc at a considerable expense in F_N/W_A. Finally, figure 8(d) shows that increases in FPR, unlike the other parameters considered in parts (a) through (c), cause both a reduction in sfc and an increase in F_N/W_A. Obviously, then, increasing the FPR is one of the keys to better engine performance. The other parameters considered in figure 8 are, to a greater or lesser degree, a mixed blessing performance-wise. Consequently, an overall measure of airplane performance such as range must be examined in order to find those engine design parameters yielding an optimum balance between sfc and engine weight.

"Thumbprint" plots, which incorporate the effects of both engine performance and weight, were made at each FPR and T_4 combination considered in this study. Representative samples of these plots are shown in figure 9(a-b). Contours of constant range increments were plotted in a BPR versus OPR coordinate system. The sideline jet noise "floor" is also plotted as a series of broken lines. Solid lines of constant sea-level-static thrust-to-gross-weight ratio F_N/W_G were also plotted. It is found from figure 9(a) that for an FPR of 1.50 and a takeoff T_4 of 2660° R total range maximizes at a value of 3127 nautical miles. An OPR of 30 and a BPR of 4 are required to maximize the range at this value. Notice, however, from the spacing of the incremental range contours that the optimum is rather flat. Considerably different values of OPR and BPR could have been selected without much range degradation.

At the peak range, the sideline jet noise after lift-off is 116.5 PNdB. To meet the 106.5 PNdB requirement of F.A.R. Part 36, the BPR must be raised from 4.0 to 5.6 with the OPR constant at 30. The resultant range (3105 n. mi.) is 22 miles less than the peak. Hence, the jet noise "floor" can be reduced by 10 PNdB with only a slight range penalty by increasing the BPR. The noise produced by the combined jet streams is a floor below which the total noise cannot be reduced. It is assumed that if machinery noise exceeds this floor, it can be attenuated below the jet noise level by acoustic treatment so that its contribution to sideline noise will be minimal for this case. A further discussion of this point will occur later.

A similar "thumbprint" plot was made for an FPR of 1.75 and a takeoff T_4 of 2660° R (fig. 9(b)). For these conditions, a peak range of 3340 nautical miles is obtained at an OPR of 31 and a BPR of 4.2. Notice that here also the range contours are widely spaced, indicating that the cycle parameters may be changed somewhat from the optimum values without much range decrement. At the peak range, the sideline noise "floor" is 102.6 PNdB - about 4 PNdB below the limit. Further investigation revealed that the cycle design parameters needed modification to meet the sideline noise requirement only at the minimum FPR considered in this study (i.e., FPR = 1.50).

The maximum ranges obtained from the "thumbprint" plots for each FPR and T_4 combination considered in this study are plotted against FPR in figure 10(a), with takeoff T_4 as a parameter. The left-hand end of these curves have been lowered slightly to reduce the full-power sideline jet noise to 106.5 PNdB. It is evident from these curves that higher fan pressure ratios can provide a significant range increase when BPR and OPR are reoptimized. The range appears to maximize at an FPR greater than 2.25. This result might have been expected from the performance sensitivity curves of figure 8. In figure 8(d), it was shown that, as FPR was increased, improvements in both sfc and specific thrust were obtained. The perturbation of no other design parameter caused a simultaneous improvement in both of these indices of engine performance.

In figure 10(b), the range results of figure 10(a) have been replotted against takeoff T_4 with FPR as a parameter. At the lowest FPR considered (FPR = 1.50), the range increases approximately linearly with T_4 at the rate of 23 nautical miles for each 100° R rise. As the FPR is increased, the slopes of these solid curves increase. For example, at an FPR of 2.25, the range increases about 43 nautical miles for each 100° R rise in T_4. The broken lines of constant BPR show that the optimum BPR increases with a temperature rise and decreases with an increase in FPR.

In the remaining parts of figure 10 (parts c through g) are shown the optimum BPR, OPR, sea-level-static total airflow, thrust-to-gross-weight ratio, and maximum engine diameter at each FPR. Takeoff T_4 is used as a parameter in these plots. In these plots, it can be seen that the optimum OPR varies only slightly with FPR, but increases significantly with a rise in T_4. The sea-level-static airflow decreases significantly as FPR is increased. This is primarily because the optimum BPR is decreasing as FPR increases. As T_4 is raised, the airflow requirements increase because of the rise in optimum BPR.

Figure 10(f) shows that the optimum sea-level-static thrust-to-gross-weight ratio F_N/W_G declines with an increase in FPR. This is primarily because the optimum BPR declines with an increase in FPR. Reducing the BPR decreases the thrust lapse from takeoff to cruise and, hence, decreases the takeoff-to-cruise thrust ratio. Since each engine is sized to provide a fixed cruise thrust and TOGW is fixed, sea-level-static F_N/W_G decreases as BPR decreases. Since the optimum BPR increases with a rise in T_4, F_N/W_G by the above reasoning also increases as T_4 is increased. For the span of engine design parameters considered in this study, F_N/W_G lies between 0.256 and 0.330. Three-engine transports now in commercial service generally have somewhat lower values of F_N/W_G when fully loaded (values range from 0.240 to 0.270).

Maximum engine diameter calculated by the method of reference 4 is largely a function of BPR. Its similar behavior can be observed by comparing the results of figure 10(g) with those of 10(c).

Engine Cycle Optimization with Turbine Cooling Bleed

The preceding section showed the maximum possible advantage of higher turbine-inlet temperature since there was no turbine cooling bleed air at any temperature. In the following data, the turbine cooling bleed schedule of figure 4 was used. FPR and T_4 were varied over the same spectrum as before without bleed. The maximum ranges obtained from a series of "thumbprint" plots are plotted against FPR in figure 11(a) for three levels of takeoff T_4. The left-hand ends of these curves have been lowered slightly, as before, to reduce the full-power sideline jet noise to 106.5 PNdB. The trends are now generally the same as without bleed except that the range separation between curves of constant T_4 is not as great as before. Also, the advantage of raising the FPR has diminished somewhat. But range still seems to maximize at an FPR greater than 2.25. Ranges obtained with this bleed schedule were from 70 to 235 nautical miles less than without bleed. The range reduction was most pronounced at higher temperatures and fan pressure ratios.

As shown in figure 11(b), range does not now improve as much as before with an increase in T_4. At an FPR of 1.50, range increases only about 10 nautical miles for a 400° R rise in T_4. Without bleed, the corresponding increase (fig. 10(b)) was about nine times as great. The incentive to strive for higher T_4 is greater at higher FPR. At an FPR of 2.25, the range increases about 60 nautical miles for the same 400° R rise in T_4.

If, instead of raising the value of T_4, it could be fixed while cooling bleed is reduced by technological advances, significant range improvements would occur, especially at high fan pressure ratios. For example, a comparison of figures 10(b) and 11(b) at an FPR of 2.25 and a takeoff T_4 of 2860° R reveals that range could be increased about 235 miles if the need for turbine cooling bleed could be entirely eliminated.

As shown in figure 11(c), the optimum BPR still declines with increases in FPR, but the introduction of a bleed schedule has reduced the BPR's from the optimum levels achieved without bleed. The optimum OPR, as before, remains approximately constant as FPR is increased, as shown by figure 11(d). The optimum OPR with bleed increases as T_4 is increased at any given FPR. The use of a bleed schedule has reduced the optimum OPR's from the levels obtained without cooling bleed. For example, a comparison of figures 10(d) and 11(d) at an FPR of 2.25 and a T_4 of 2860° R shows that OPR is reduced from an optimum of 38 without bleed to an optimum of 27 with the bleed schedule used in this study.

The sea-level-static F_N/W_G, maximum engine diameter, and sea-level-static airflow all decrease as FPR is increased, as shown in figure 11(e-g). Raising the level of T_4 at a given FPR increases the value of each of these variables. The reasoning is the same as in the previous discussion for no bleed. The F_N/W_G, maximum engine diameter, and airflow are now less than they were without bleed because the optimum BPR has been reduced.

Effect of Engine Drag on Airplanes with Cooled Engines

Up to this point, it has been assumed that the overall airplane lift-drag ratio L/D did not change (i.e., nacelle drag was constant at some reference level) as engine diameter was changed. This assumption is probably optimistic but might be approached by re-area-ruling the airplane each time engine size is changed. Figure 12 shows the range variation with FPR for a nacelle drag schedule which varies with engine maximum diameter (drag schedule shown in fig. 5). Takeoff T_4 and chargeable bleed were fixed at 2660° R and 6 percent, respectively. BPR and OPR were not reoptimized for this drag schedule, but were varied with FPR according to the schedules of figure 11(c) and (d). The mid-temperature curve of figure 11(a) is replotted here for comparison. Note the cross over at FPR = 1.7 for the reference diameter. Since the optimum engine maximum diameter decreased with increases in FPR, the range increases more rapidly with FPR when the nacelle drag schedule of figure 5 is used. Hence, giving increased importance to the installation drag effect reinforces the conclusion that FPR should be increased as much as is feasible up to some limit beyond an FPR of 2.25.

Noise Constraints Applied to Engines with Cooling Bleed

The range curve from figure 11(a) for a takeoff T_4 of 2660° R has been repeated as the upper curve in figure 13(a). With acoustically untreated nacelles, both the total approach noise (fig. 13(b)) and total sideline noise (fig. 13(c)) limits of F.A.R. Part 36 are exceeded. Even with acoustic treatment, it appears doubtful that the approach noise requirement can be met with other than a single-stage fan engine for the 15 PNdB maximum suppression assumed.

Range penalty with acoustically treated nacelles. - When acoustic treatment estimated to reduce approach fan machinery noise by about 10 PNdB was applied to the inlet and duct, range was reduced by 40 to 80 nautical miles, as shown by the lower curve of figure 13(a). Treatment (as indicated in fig. 3) included the addition of one splitter ring to the inlet together with both inlet and duct acoustic wall lining. Treatment weight, and hence range penalty, was assumed to increase with engine maximum diameter. Although these range penalties were for a case where takeoff T_4 was 2660° R, practically identical penalties were obtained for the other values of T_4 considered in this study.

Approach noise. - The middle band of curves in figure 13(b) represents the total noise when both inlets and ducts are acoustically treated. The upper boundary of the band represents a 10 PNdB reduction in machinery noise, while the lower boundary corresponds to a 15 PNdB reduction. The 15 PNdB suppression of machinery noise represents the approximate maximum reduction that can presently be obtained with multiple inlet splitter rings. The area below the range curve for acoustically treated nacelles (lower curve, fig. 13(a)) is shaded to indicate that additional range penalties will be incurred if more than one splitter ring is used.

Acoustic treatment of the nacelle, of course, does not reduce jet noise (the bottom curve of fig. 13(b)). Although jet noise makes practically no contribution to the total untreated approach noise, it does make a discernible contribution to the total noise when the machinery noise is suppressed. Hence, the band of total suppressed noise plotted in figure 13(b) does not lie 10 to 15 PNdB below the untreated noise curve for single-stage fans. For the two-stage fans, though, the treated machinery noise exceeds the jet noise "floor" by enough to make the machinery noise practically equal to the total noise. For the two-stage fans, in other words, the treated total noise band does lie almost 10 to 15 PNdB below the untreated noise curve. Although figure 13(b) was plotted for a takeoff T_4 of 2660° R, the curves plotted for other temperatures considered herein are little different and, for brevity, are not shown.

From figure 13(b), it appears that only treated single-stage fan engines can meet the F.A.R. Part 36 approach noise limit of 106.5 PNdB for the maximum suppression of 15 PNdB assumed in this report. If the number of fan stages is fixed at one, the approach noise increases slightly as design FPR is increased. But this is rather insignificant when compared to the noise rise that occurs when the transition is made from one to two fan stages. This transition is postulated in this study to occur at an FPR of 1.7.

It is well to remember that the abscissa of figure 13(b) is design FPR although during approach the engines are each throttled back to 12 000 pounds thrust at less than design FPR. For example, for a design FPR of 1.50, the FPR during approach is 1.24. Likewise, for a design FPR of 1.70, the throttled-back approach FPR is 1.33. The untreated approach noise curve of figure 13(b) is essentially a replot of figure 6 with adjustments made to account for the fact that the operating FPR in approach is different from the design FPR. (It should be acknowledged that the science of predicting engine noise, particularly that from the turbomachinery, is quite rudimentary, and all of these cited noise levels are estimates having some band of uncertainty.)

<u>Sideline noise after lift-off</u>. - The sideline noise immediately after a lift-off at maximum thrust is plotted against FPR in figure 13(c). It is evident that with acoustically untreated nacelles the F.A.R. Part 36 requirement of 106.5 PNdB is exceeded. With acoustic treatment, it is apparent from the middle band of curves that all of the single-stage fans and many of the two-stage fans meet the sideline noise requirement.

Both the upper curve for untreated nacelles and the middle band of values for treated nacelles in figure 13(c) are total noise curves obtained by the addition of the machinery and jet noise. At the low end of the FPR spectrum, the jet noise (bottom curve, fig. 13(c)) is the predominant noise source, especially when the nacelles have been acoustically treated to suppress fan machinery noise. For single-stage fan engines, the total noise with treated nacelles is only slightly greater than the jet noise "floor." For untreated single-stage fan engines, the machinery noise exceeds the jet noise as FPR is increased beyond 1.63. For two-stage fan engines with 10 PNdB of machinery noise suppression (the upper bound of the band), the jet and machinery noises are about equal at an FPR of 1.70, but machinery noise becomes predominant as FPR is increased. For two-stage fan engines with 15 PNdB of machinery noise suppression (the lower bound of the band), the fan machinery noise never clearly predominates over the jet noise. In fact, the jet noise predominates up to an FPR of about 1.90. Beyond this, however, the machinery and jet noises appear to be about equal.

It is apparent from these curves that with a given amount of acoustic treatment the sideline noise requirement of F.A.R. Part 36 is easier to meet than the approach noise requirement. It is also apparent that with treated nacelles the sideline noise produced by single-stage-fan engines actually decreases somewhat as FPR is increased. (The opposite trend was observed during approach.) It can be concluded, then, that increasing the FPR to the limit for single-stage fans with treatment benefits both range and sideline noise while slightly penalizing approach noise.

Summary of range results for acoustically treated engines meeting F.A.R. Part 36 noise requirements. - In figure 14(a), range is plotted against FPR for the single-stage fans which have received acoustic treatment to reduce fan machinery noise 10 PNdB and thus at least meet, and in many cases surpass, the F.A.R. Part 36 requirements. The FPR goes only as high as 1.7, the postulated upper limit for one-stage fans, because two-stage fans cannot meet the approach noise limit with the 15 PNdB maximum suppression assumed in this study. A plot like figure 14(a) illustrates the importance of choosing the highest possible FPR that the noise constraints will permit. For instance, range is improved approximately 170 nautical miles by increasing the FPR from 1.5 to 1.7.

Figure 14(b) shows more clearly how much the range increases as takeoff T_4 is increased at fixed levels of FPR. The advantage of higher temperature engines increases as FPR is increased, but even at the maximum FPR that can be considered with noise constraints (i.e., FPR = 1.7), range increases only about 8 nautical miles for each 100° R rise in temperature. An improved bleed schedule, however, would show more benefit from an increase in T_4. Lines of constant BPR (broken lines) are also plotted on figure 14(b). BPR tends to optimize at a higher value as T_4 is increased and FPR is reduced.

CONCLUDING REMARKS

A preliminary parametric engine study was made for an advanced technology transport incorporating the Whitcomb supercritical wing. Cruise was chosen to be at Mach 0.98 at an initial cruise altitude of 40 000 feet. Advanced engine weight technology compatible with mid-decade introduction into regular commercial service was assumed. A takeoff gross weight (TOGW) of 386 000 pounds was selected for this 300-passenger airplane in order to provide a range of about 3000 nautical miles. As the engine design parameters were varied, range (the airplane figure of merit) was allowed to vary. Only three-engine airplanes were considered in this study.

A spectrum of fan pressure ratios (FPR) varying from 1.50 to 2.25 was considered. At each FPR, bypass ratio (BPR) and overall pressure ratio (OPR) were optimized for maximum range at three levels of turbine-inlet temperature (i.e., takeoff T_4's of 2460, 2660, and 2860° R). Engine weight was assumed to vary as a function of BPR, OPR, T_4, and airflow. Since TOGW, payload, and airframe weight (i.e., OEW minus installed engine weight) were fixed, the sum of total fuel weight and installed engine weight also remained constant. Changes in engine weight, therefore, caused the total fuel weight to vary.

Point-design performance calculations were made for cruise, but simplifying approximations were made to determine takeoff operating conditions. Despite the approximations, it is felt that the resulting trends are valid and point the way toward selection of an engine.

One of the major observations that can be made from this study is that FPR's greater than 2.25 (the maximum considered) are needed to maximize range. If the FPR is increased from 1.50 to 2.25, range can be increased by approximately 300 to 400 nautical miles, depending on the choice of T_4 and turbine-cooling bleed schedule. Generally, the greatest improvements are obtained with the highest values of T_4 and the lowest bleed schedule. The optimum BPR decreases as FPR is increased. The OPR, which also had the freedom to vary, remained nearly constant for any given level of T_4.

As the FPR is increased, the engine maximum diameter tends to decrease. In the major part of the study, it was assumed that the airplane L/D remained constant despite these engine size changes. A perturbation to the basic study was made, however, in which the nacelle drag was allowed to change linearly about some reference level with diameter, thereby changing the airplane L/D. This approach merely reinforces the finding about the desirability of higher FPR's. Since the engine diameter decreases as FPR is increased, airplane L/D must increase. Hence, range must increase even faster than in the basic study. In fact, with this particular nacelle drag schedule, the range improvement obtained by increasing the FPR from 1.50 to 2.25 can be increased by an additional 67 percent over the results obtained with the fixed L/D schedule used in the major part of the study.

Higher T_4's produced range increases at any given FPR. Higher BPR's and OPR's were required to realize the full potential of the higher T_4's. The amount of range improvement produced by a given increase in T_4 was found to be a function of both the FPR and the turbine-cooling bleed schedule. For instance, at an FPR of 2.25 the range increased 170 miles as T_4 was increased over the 400° R span considered herein with no bleed. When a bleed schedule representative of present-day technology was used, however, a range improvement of only 60 miles was obtained. At the lower end of the FPR spectrum (i.e., FPR = 1.50), much lower range improvements were obtained for a given temperature rise. Hardly any improvement was obtained with the bleed schedule representative of present-day technology.

If instead of raising T_4, it could be fixed while cooling bleed is reduced by technological advances, significant range improvements would occur, especially at the higher FPR's. For instance, the range could be increased 235 miles at an FPR of 2.25 and a takeoff T_4 of 2860° R if the need for any turbine cooling bleed could be entirely eliminated. As with an increase in T_4, a reduction in bleed increases the optimum BPR and OPR.

The sideline (lift-off) and approach noise constraints of F.A.R. Part 36 were applied to the range-optimized engine results to determine if the choice of an optimum engine would be affected. It was found that neither of these noise requirements could be met with any of the engines considered without inlet and duct acoustic treatment. Even with the maximum acoustic treatment assumed in this report (15 PNdB), it appears doubtful that the approach noise requirement can be met with other than a single-stage fan engine (based on the noise characteristics of present-day multistage fans). The maximum FPR that can be obtained with a single fan stage can vary somewhat depending on fan design techniques, but a value of 1.7 is an approximate upper limit. Limiting the engine choice to those with only one fan stage is unfortunate because of the significant improvement in range that can be obtained with higher FPR's that can only be obtained by multi-staging.

The weight penalty of the acoustic treatment was estimated to be about 500 to 600 pounds per engine. This weight includes the inlet and duct wall treatment and the addition of a splitter ring to the inlet. The addition of this amount of weight to the engines can be translated into a range penalty of about 80 miles (less than 3 percent of the total range).

Although there is a range of choice in the selection of an optimum cycle meeting the noise requirements, the optimum is much more clear-cut once T_4 and a cooling bleed have been specified. If we choose a conservative T_4 in the middle of the range considered (i.e., a takeoff T_4 of 2660° R) and assume that cooling and metallurgical technologies do not advance, the BPR and OPR will optimize at 3.8 and 24.6, respectively, when the FPR is limited to 1.7 by noise considerations. The sea-level-static total airflow per engine should be 1100 pounds per second for the 386 000-pound airplane of this study. A sea-level-static thrust-to-gross-weight ratio (F_N/W_G) of 0.285 should provide good takeoff and initial climbout performance relative to three-engine transports now in commercial service which have F_N/W_G's lying between 0.240 and 0.270. The maximum diameter of this engine is 80 inches and occurs at the rear flange. With a bleed schedule characteristic of existing technology, there is little incentive to increase T_4 since range increases by only 10 miles for each 100° R rise in temperature.

If technological advancements could somehow completely eliminate the need for cooling bleed at a takeoff T_4 of 2660° R, the BPR would optimize at 4.5 instead of 3.8 and the OPR would optimize at 31.0 instead of 24.6. The elimination of bleed would increase the range by about 150 nautical miles (almost 5 percent). Without bleed, the incentive to increase T_4 would also be increased. Range would increase about 60 miles for each 100° R rise in T_4 - about six times faster than with the present-technology bleed schedule.

These optimum values of BPR and OPR were obtained with airplane L/D assumed to remain constant as engine diameter changed. If engine drag was assumed to increase with diameter, lower BPR's would be favored, but the noise goals would prevent a significant reduction in BPR.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 8, 1971
126-15-13

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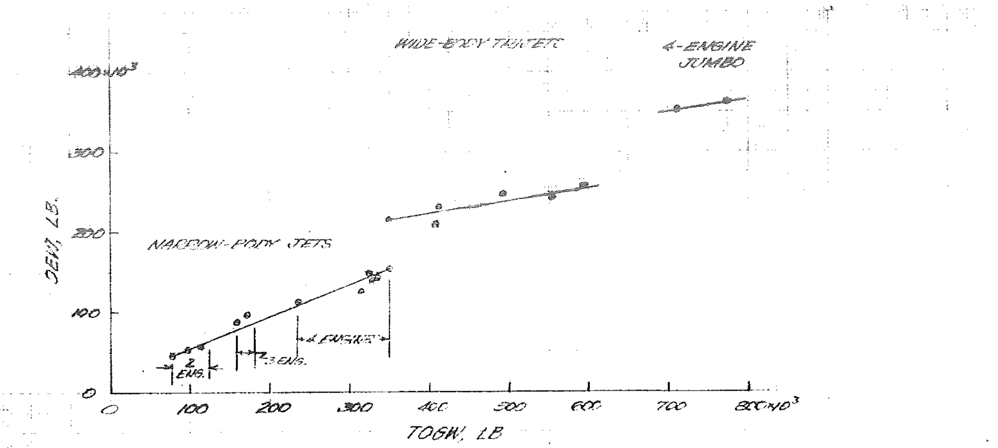


FIGURE 1.— WEIGHTS OF TURBOFAN-POWERED SUBSONIC TRANSPORTS. (DATA FROM REF. 1)

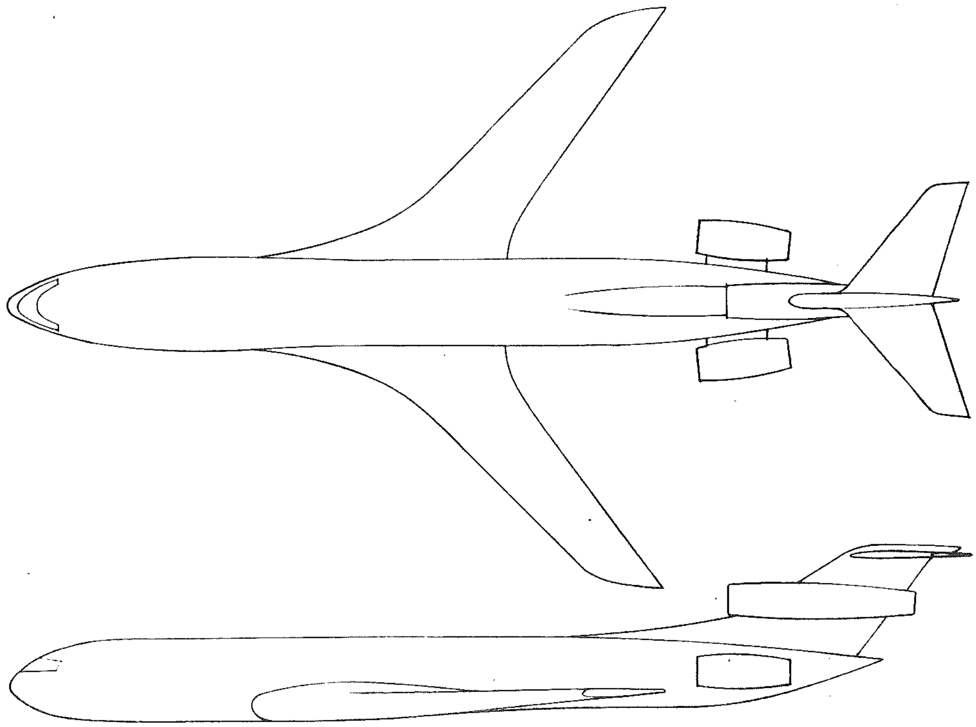


FIGURE 2.— SKETCH OF CONCEPTUAL MACH 0.98 TRI-JET TRANSPORT.

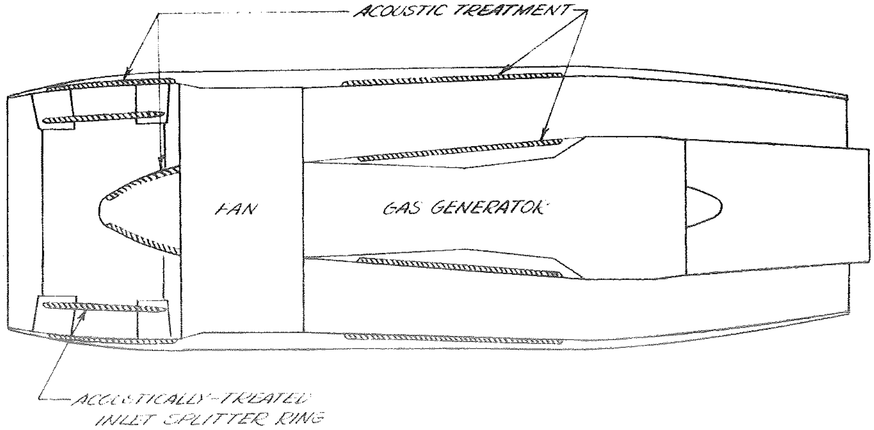


FIGURE 3.— SKETCH OF TURBOFAN ENGINE INSTALLATION WITH ACOUSTIC TREATMENT.

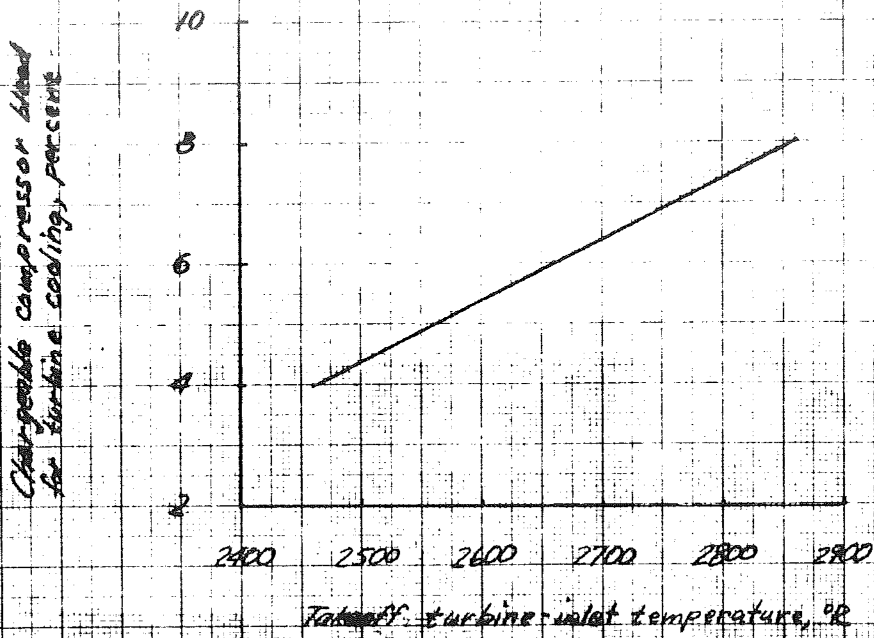


Figure 4.- Schedule of chargeable compressor bleed used for turbine cooling versus takeoff turbine-inlet temperature

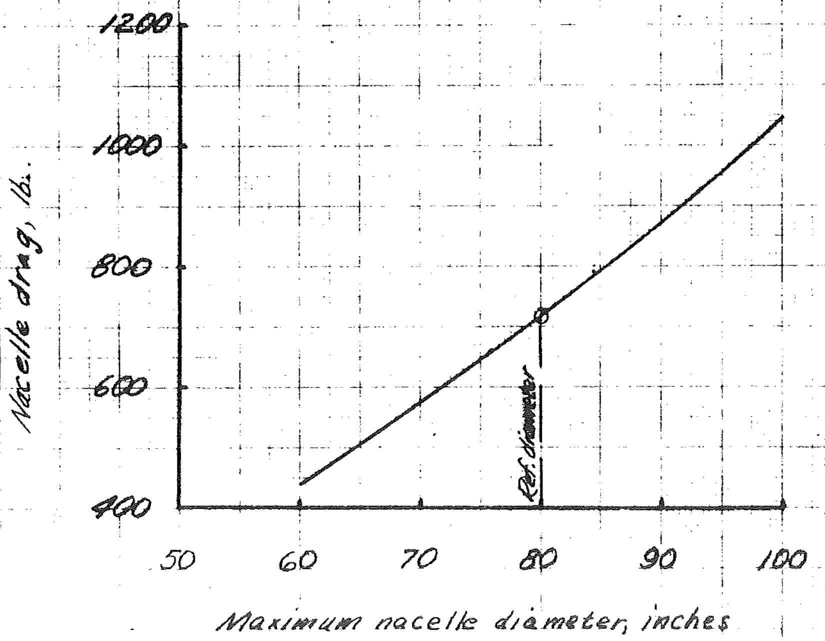


Figure 5.- Drag per nacelle versus maximum nacelle diameter for a cruise Mach number of 0.98 at 40000-foot altitude.

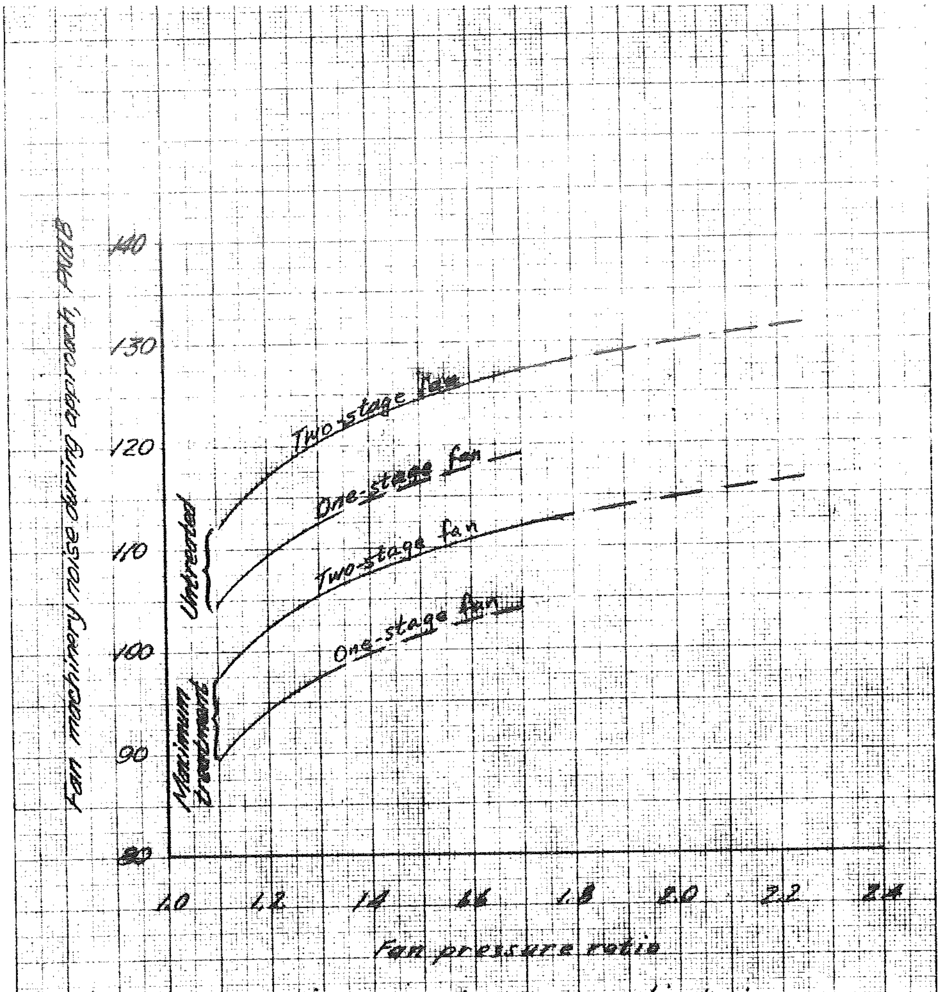


Figure 6.- Fan noise versus fan pressure ratio during approach. Total net thrust for three engines = 36 000 lb. Altitude = 370 ft, Mach number = 0.203, 3° glide slope.

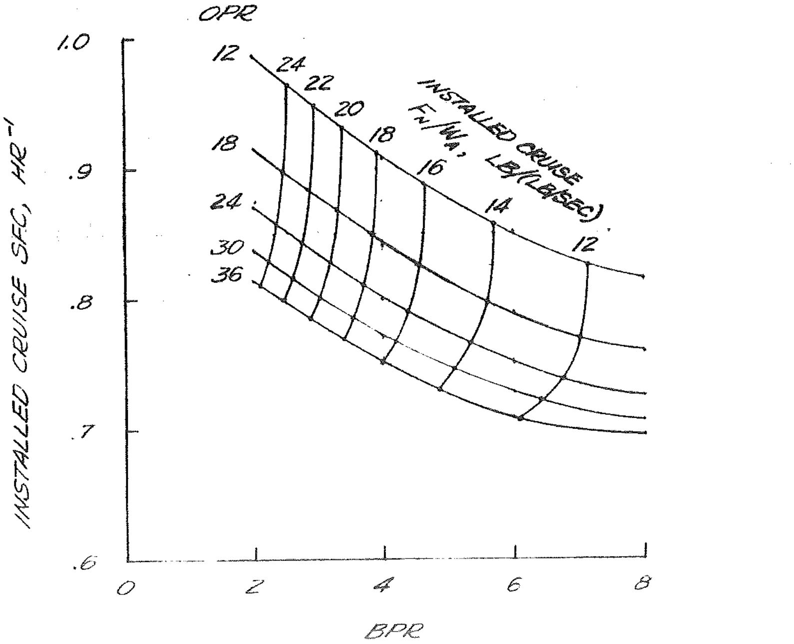


FIGURE 7. — CRUISE CYCLE PERFORMANCE FOR CRUISE AT MACH 0.98 AT 40 000 FT; FPR = 1.5, $T_{4_{CR}}$ = 2460°R; NO TURBINE COOLING BLEED.

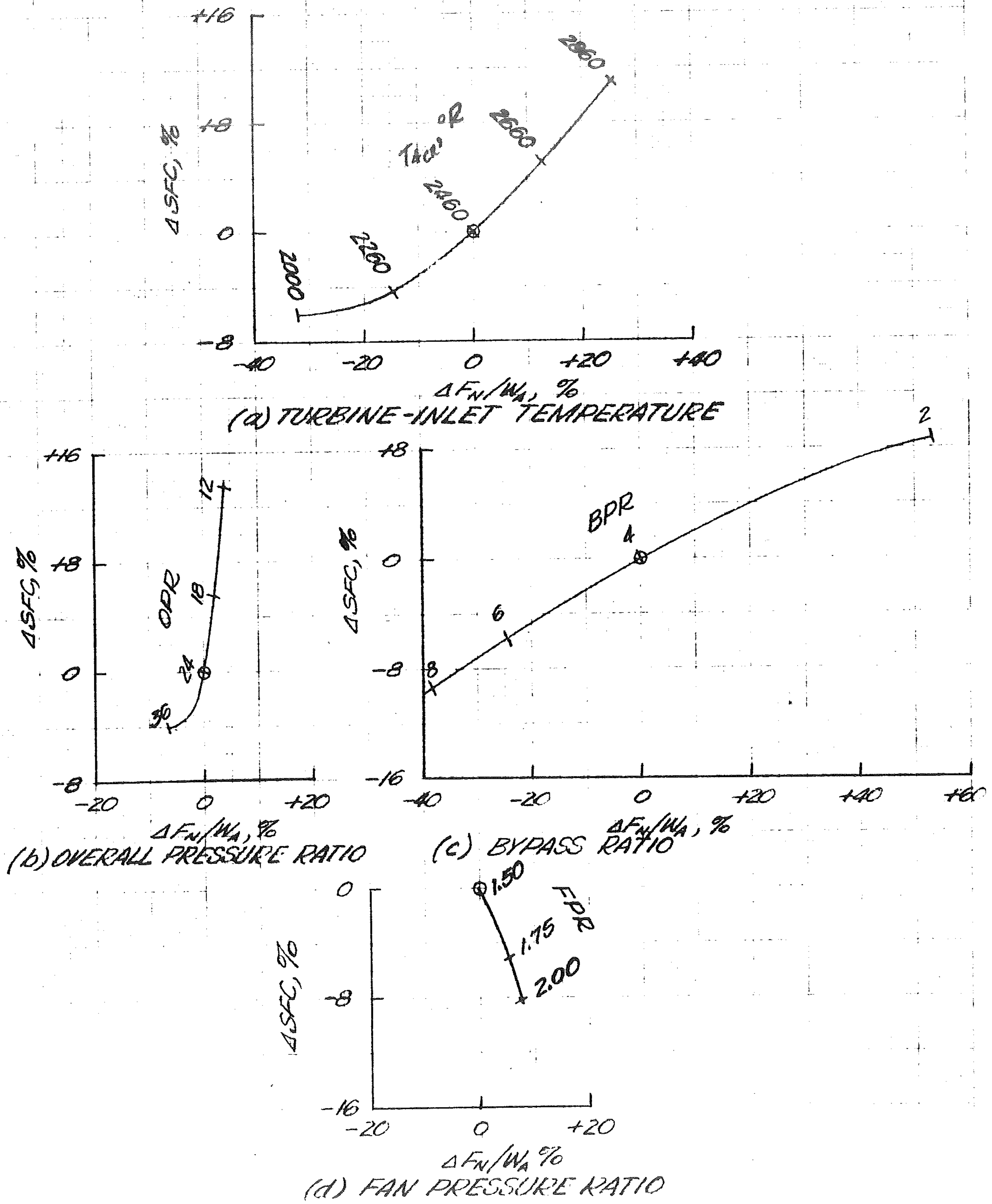
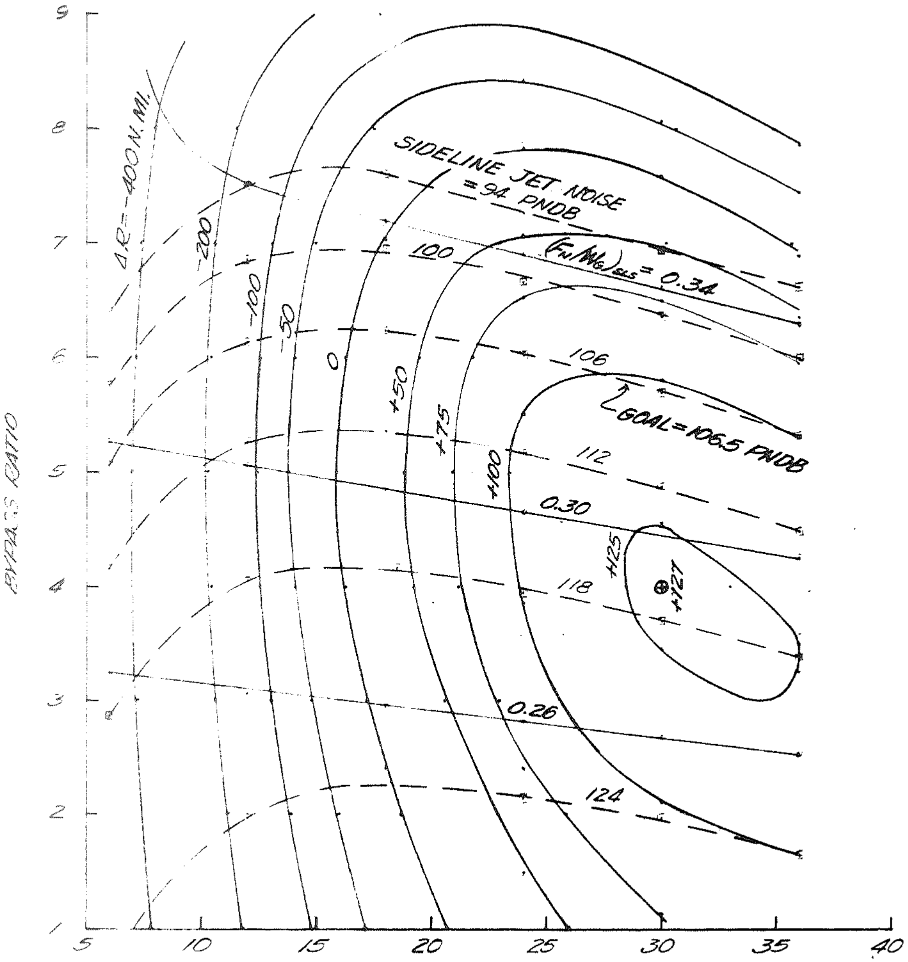
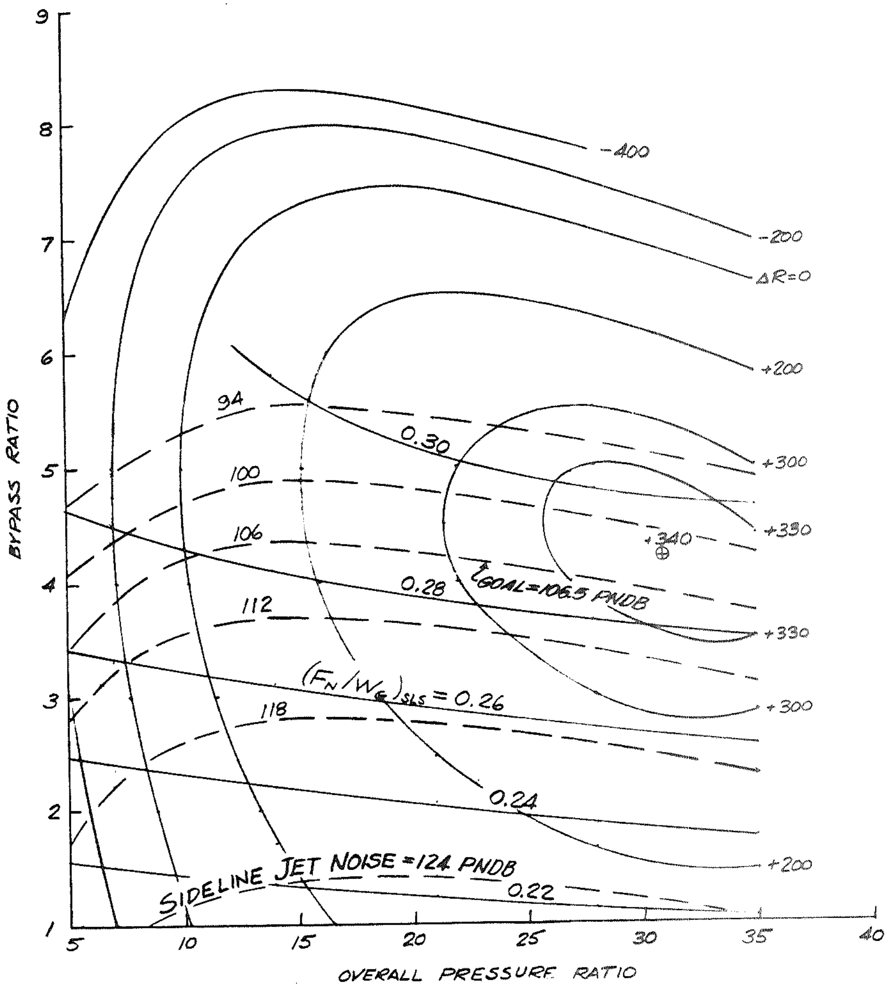


FIGURE 8. - EFFECT OF A CHANGE IN ENGINE VARIABLES ON MACH 0.98 CRUISE PERFORMANCE. REFERENCE T_{4ck} = 2460 °R, OPR = 24, BPR = 4, FPR = 1.50. NO TURBINE-COOLING BLEED.



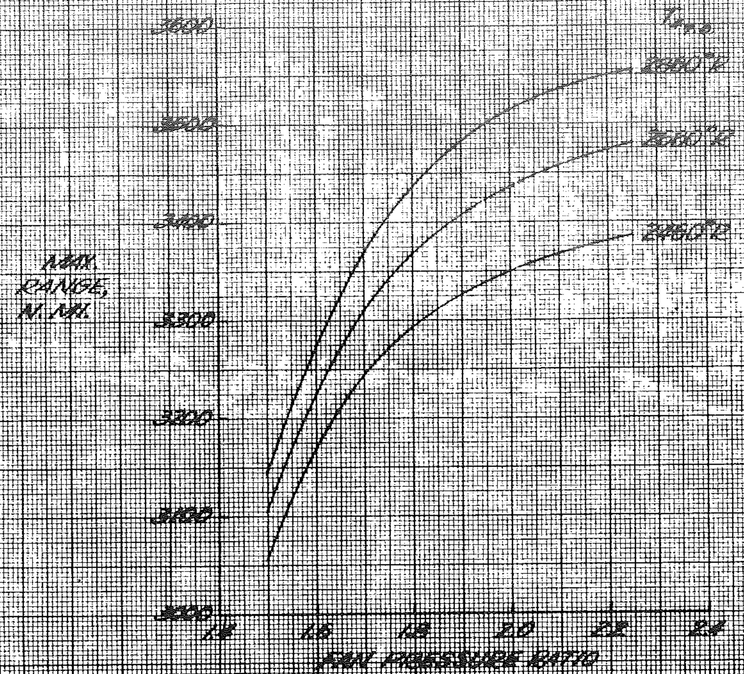
(a) FAN PRESSURE RATIO = 1.50.

FIGURE 9.—"THUMBPRINT" PLOTS. TAKEOFF T_4 = 2660°R, CRUISE T_4 = 2460°R, R_{REF} = 3000 N. MI., CRUISE M = 0.98, NO TURBINE COOLING BLEED. JET NOISE CALCULATED AT FULL POWER AFTER LIFT-OFF ON A 0.25-N.-MI. SIDELINE.



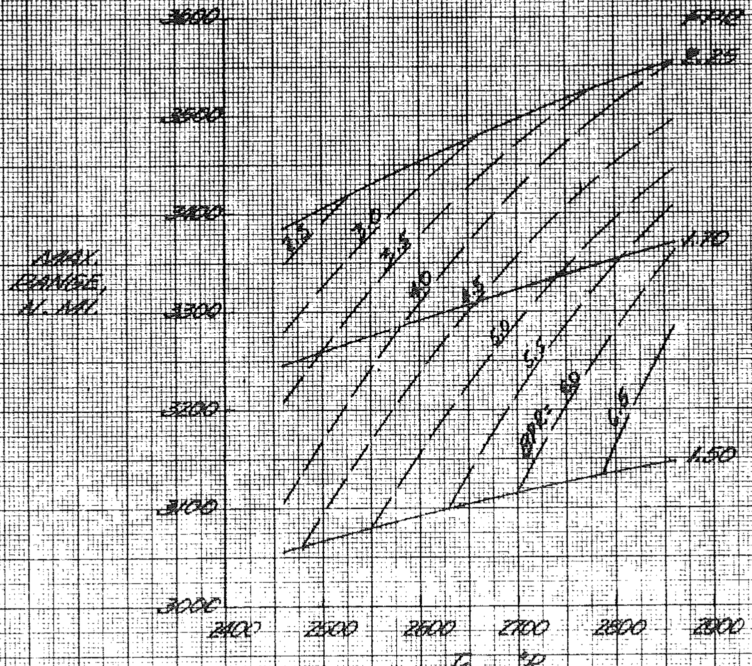
(b) FAN PRESSURE RATIO = 1.75.

FIGURE 9.—(CONCLUDED)



(a) RANGE VS. FAN PRESSURE RATIO

FIGURE 10. - VARIATION OF RANGE WITH NO BLEED FOR TURBINE COOLING; CRUISE AT MACH 0.98 AT 40 000 FT; TOGW = 386 000 LB; 300 PASSENGERS.



(b) RANGE VS. TAKEOFF TURBINE-INLET TEMPERATURE

FIGURE 10. - (CONTINUED)

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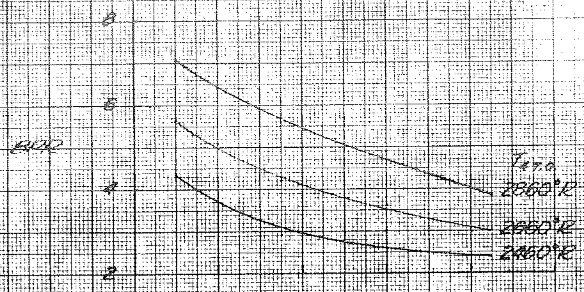
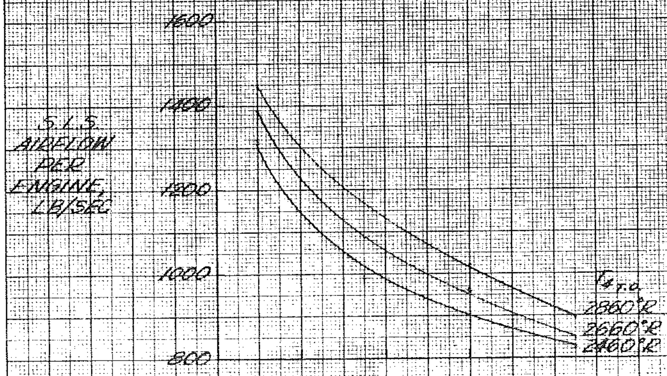


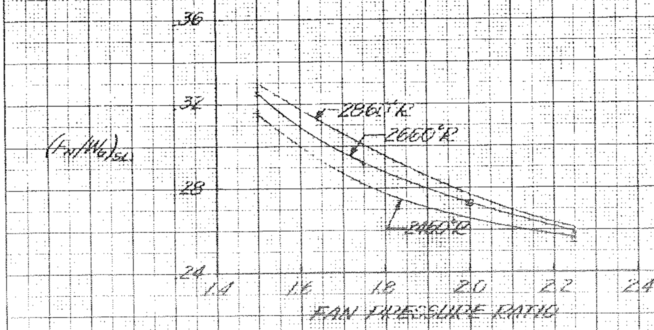
(c) OPTIMUM BYPASS RATIO

(d) OPTIMUM OVERALL PRESSURE RATIO

FIGURE 10 - (CONTINUED)

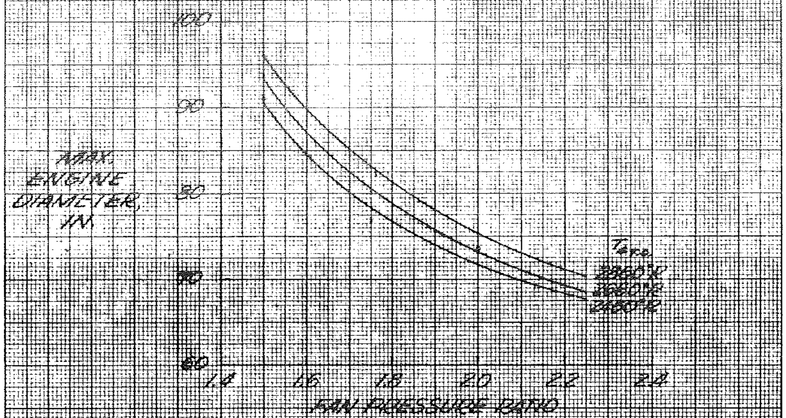


(e) SEA-LEVEL-STATIC AIRFLOW



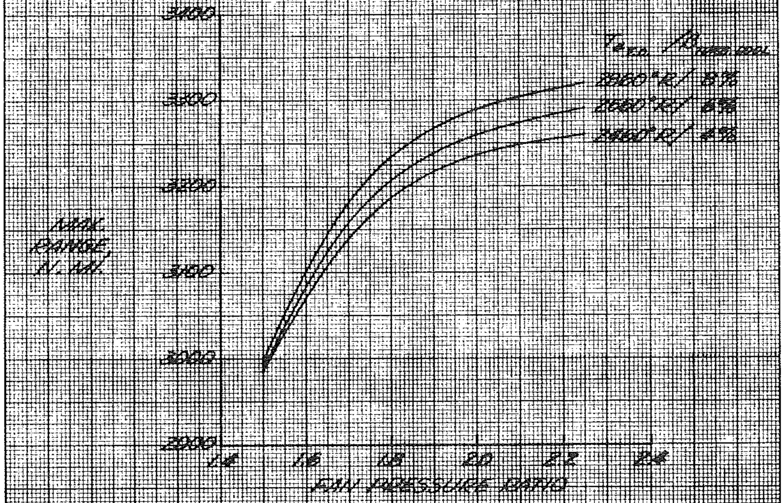
(f) SEA-LEVEL-STATIC THRUST/GROSS WEIGHT

FIGURE 10 - (CONTINUED)



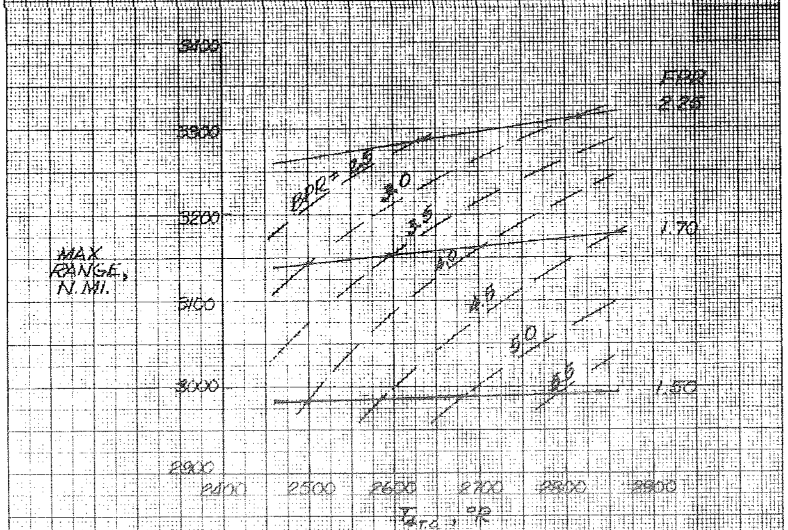
(g) MAXIMUM DIAMETER OF RANGE-OPTIMIZED ENGINES.

FIGURE 10.—(CONCLUDED)



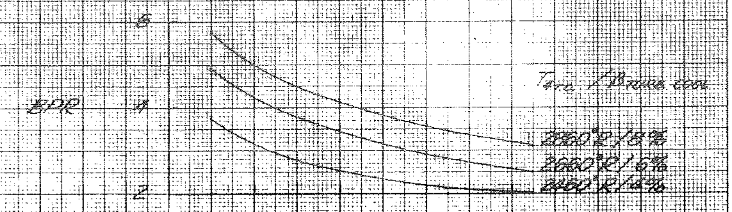
(a) RANGE VS. FAN PRESSURE RATIO

FIGURE 11.—MAXIMIZATION OF RANGE WITH TURBINE-COOLING BLEED SCHEDULE OF FIG. 4; CRUISE AT MACH 0.98 AT 40 000 FT; TOGW = [illegible] 000 LB; 300 PASSENGERS.

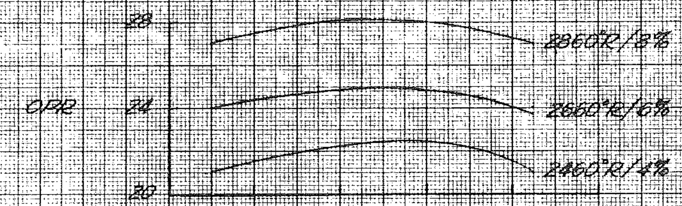


(b) RANGE VS TAKEOFF TURBINE-INLET TEMPERATURE

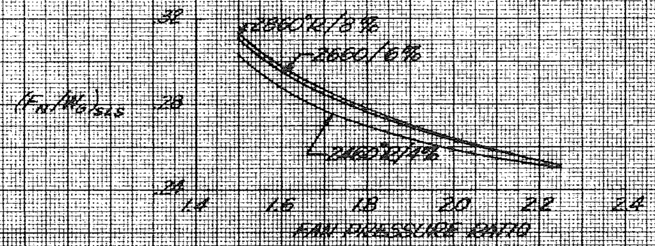
FIGURE 11.—(CONTINUED)



(c) OPTIMUM BYPASS RATIO

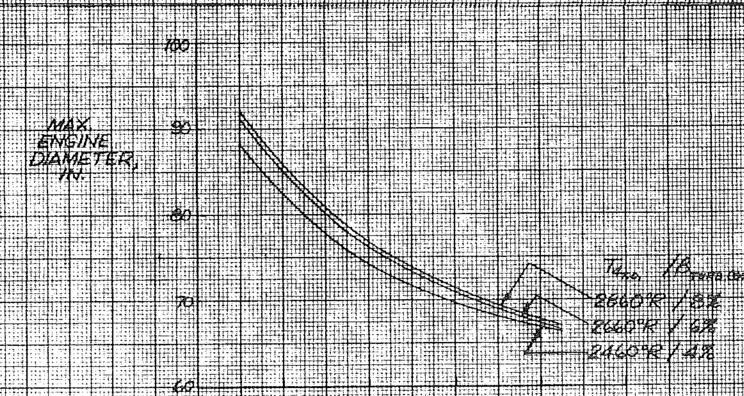


(d) OPTIMUM OVERALL PRESSURE RATIO

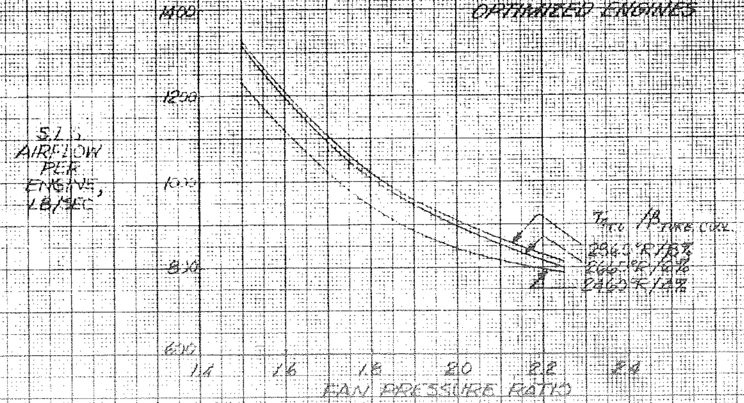


(e) SEA-LEVEL-STATIC THRUST/GROSS WEIGHT

FIGURE 11. – (CONTINUED)



(f) MAXIMUM DIAMETER OF RANGE-OPTIMIZED ENGINES



(g) SEA-LEVEL-STATIC AIRFLOW

FIGURE 11. – (CONCLUDED)

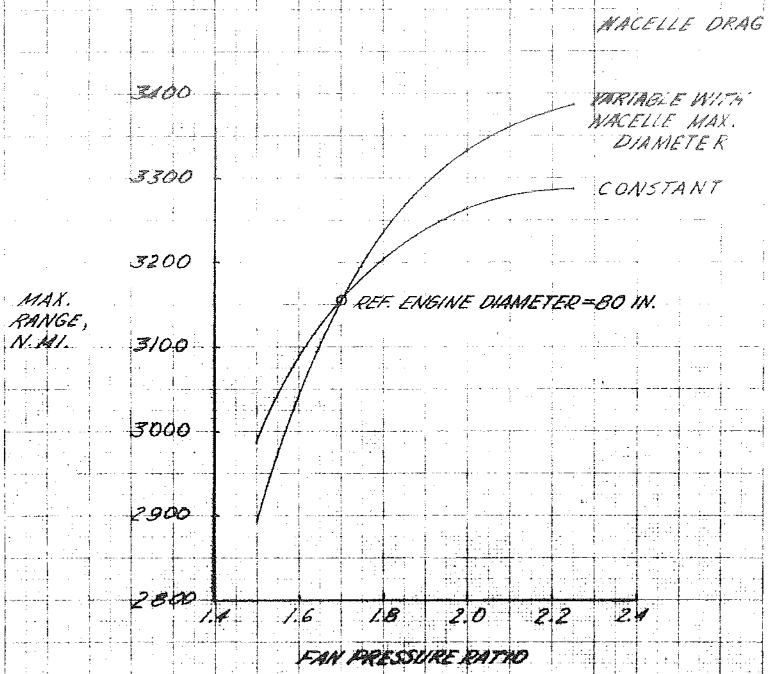


FIGURE 12.- EFFECT OF NACELLE DRAG SCHEDULE ON RANGE OPTIMIZATION; CRUISE AT MACH 0.98 AT 40 000 FT; TAKEOFF T_4 = 2660°R WITH 6% BLEED. TOGW = [illegible] LB, [illegible] PASSENGERS.

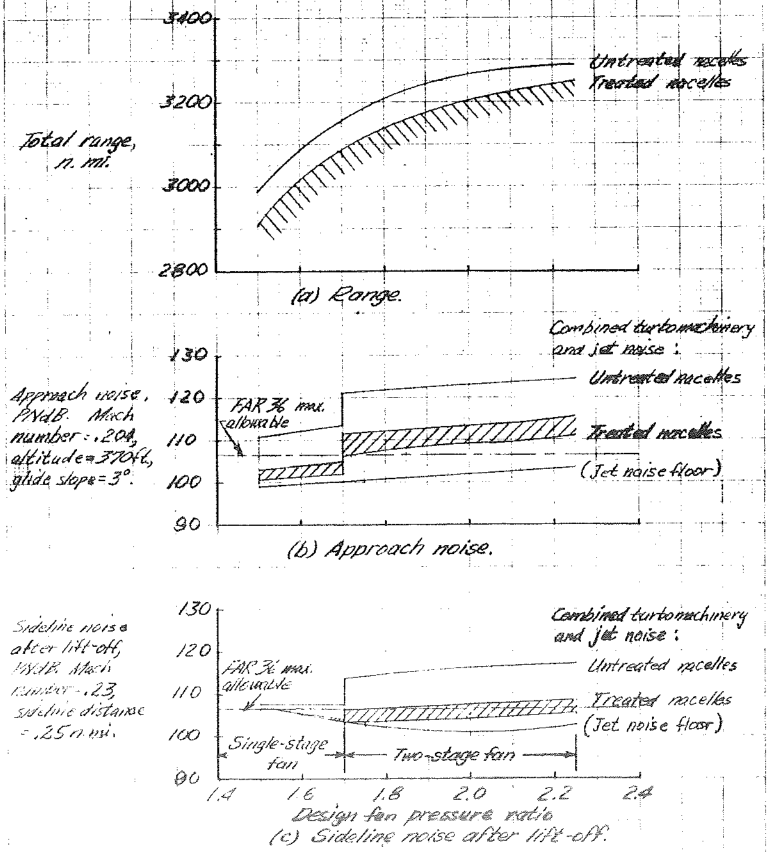
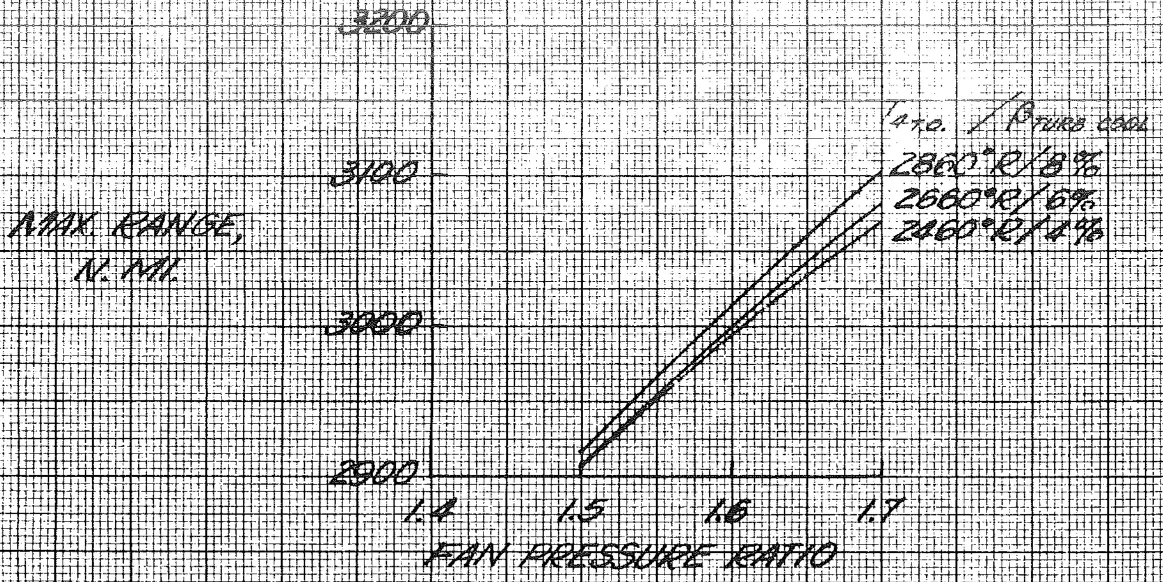
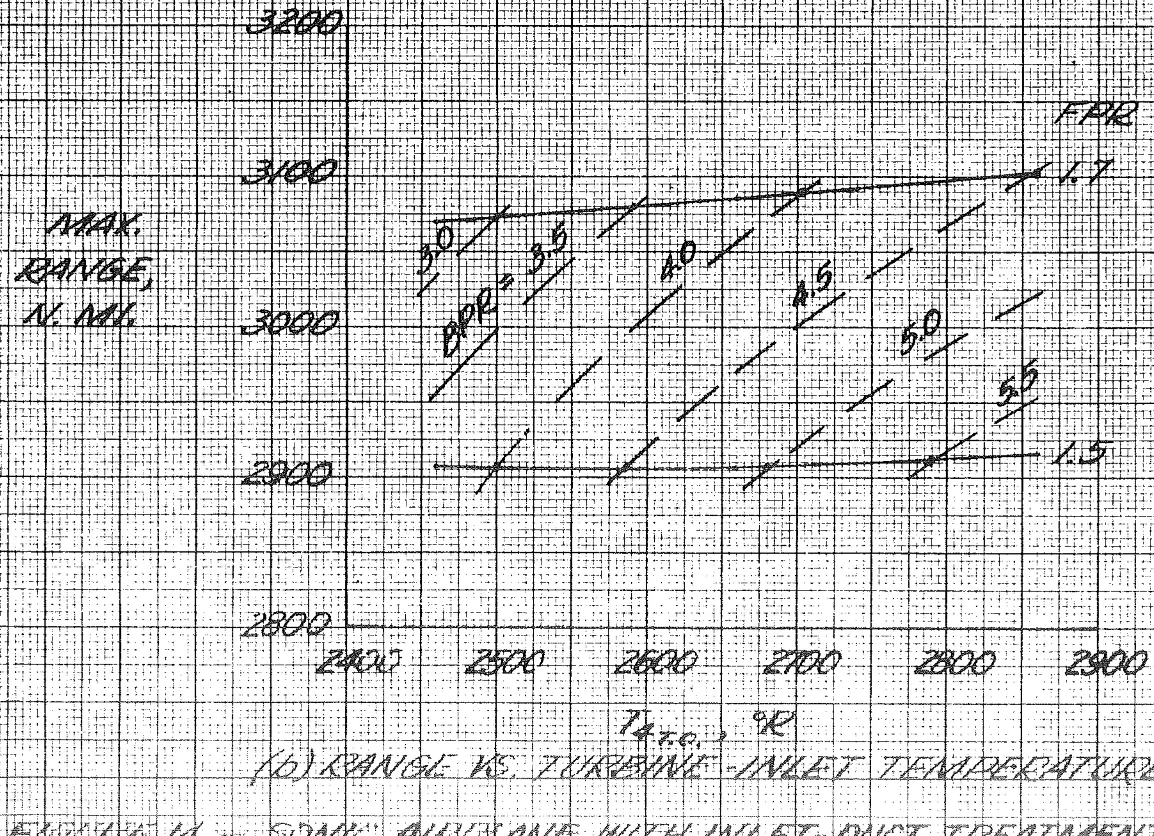


Figure 13.– Range and noise both with and without nacelle acoustic treatment. Takeoff T_4 = 2660°R, turbine cooling bleed = 6%.



(a) RANGE VS. FAN PRESSURE RATIO



(b) RANGE VS. TURBINE-INLET TEMPERATURE

FIGURE 14. - SONIC AIRPLANE WITH INLET-DUCT TREATMENT TO MEET FAR 36 NOISE REQUIREMENT; CRUISE AT M=0.98, ALT.=40 000 FT; WITH TURBINE COOLING BLEED.